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Solar water heaters with phase change material thermal energy storage medium: A review

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ABSTRACT

Latent heat thermal energy storage is one of the most efficient ways to store thermal energy for heating water by energy received from sun. This paper summarizes the investigation and analysis of thermal energy storage incorporating with and without PCM for use in solar water heaters. The relative studies are classified on the basis of type of collector and the type of storage used i.e. sensible or latent. A thorough literature investigation into the use of phase change material (PCM) in solar water heating has been considered. It has been demonstrated that for a better thermal performance of solar water heater a phase change material with high latent heat and with large surface area for heat transfer is required.

Contents

1. Introduction

Energy is the backbone of human activities. The importance of energy in economic development is very critical as there is a strong relationship between energy and economic activity. Historically fossil fuel in its solid phase, i.e. wood and coal, has been the prime source of energy. The increment in global energy demands due to population growth and 20th century industrial revolution leads fossil fuel through a transitional phase. It is being widely realised that for sustainable development presently used energy mediums such as fossil fuel and nuclear power have to be quickly replaced by renewable energy sources. The latter are sustainable and have the potential to meet present and future projected global energy demands without inflicting any environmental impacts. Renewable energy sources such as solar, wind, hydropower and biogas are potential candidates to meet global energy requirements in a sustainable way.

Solar energy applications require an efficient thermal storage. Hence, the successful application of solar energy depends, to a large extent, on the method of energy storage used. The latent heat of melting is the large quantity of energy that needs to be absorbed or released when a material changes phase from solid state to liquid state or vice-versa. The magnitude of the energy involved can be demonstrated by comparing the sensible heat capacity of concrete (1.0 kJ/kg K) with the latent heat of a phase change material (PCM), such as paraffin wax (154 kJ/kg). It is obvious that any energy storage systems incorporating PCM will comprise significantly smaller volume when compared to other materials storing only sensible heat. A further advantage of latent heat storage is that heat storage and delivery normally occur over a fairly narrow temperature range the phase change temperature.

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Efficient and reliable storage systems for thermal energy are an important requirement in many applications. One of the areas where solar energy is used extensively is water heating. Solar water heaters are getting popularity [1–3] since they are relatively inexpensive and simple to fabricate and maintain. They are a viable supplement or alternative to electric or gas hot water production. These avoid the harmful greenhouse gas emissions associated with electricity production. Hot water is required for bathing, drinking and washing purposes in houses, industries and commercial organizations. During a 20-year period, one solar water heater can avoid over 50 tons of carbon dioxide emissions. Depending on climate and requirement, a properly designed, installed, and maintained solar water heater can meet from half to nearly all the hot water demand. It can operate in any climate; performance varies depending, in part, on how much solar energy is available at the site, but also on how cold the water coming into the system.

The total installed capacity of solar hot water systems in the year 2007 was approximately 154 GW. China is the world leader in their deployment with 70 GW installed as of 2006 and a long term goal of 210 GW by 2020. Israel and Cypress are the per capita leaders in the use of solar hot water systems with over 90% of homes using them.

Fortunately, India is blessed with abundant of solar radiation and is available almost whole year throughout the country. India receives 5000 trillion kWh per annum of solar radiation with a daily average of 4–7 kW h m^{-2}. The maximum solar radiation is received at Jodhpur i.e. 20.97 MJ m^{-2} day^{-1} and the minimum value obtained at Shillong i.e. 15.90 MJ m^{-2} day^{-1}. The most arid parts of the country receive maximum radiation, i.e. 7200–7600 MJ m^{-2} per annum, semi arid areas receive 6000–7200 MJ m^{-2} per annum and the amount received in mountainous regions is around 6000 MJ m^{-2} per annum [5]. The ambient temperature in northern and central parts of the country varies between 2 °C (minimum) and 25 °C (maximum) in winters. Governmental promotions increased the collecting area to 1×10^7 m^2 against total potential of 1.4×10^9 m^2 collector area [4]. However, the use of solar energy still remains far less prevalent than equivalent in Japan and Israel. Therefore, much room remains for elevating the use of solar water heater and increasing its popularity and reliability.

2. Classification of solar energy collectors

On the basis of the type of energy collection; solar energy collectors can be classified into three types flat plate, evacuated tube and concentrating collectors; on the basis of mode of operation they can be broadly classified into two types viz. active and passive. Solar water heating systems can be either active or passive depending on their operating conditions. An active system uses an electric pump to circulate the heat transfer fluid whereas a passive system has no pump. These can further classified into direct and indirect types. A direct solar water heating system circulates household water through collectors and is not appropriate in climates in which freezing temperatures occur; indirect type uses a heat transfer fluid. These active or passive modes of energy transport can be used in any of the flat plate, evacuated or concentrating type of collector.

To evaluate the thermal performance of a solar water heater; collector efficiency curve is an important physical property of a solar collector. The efficiency of a collector is defined as the ratio of the amount of energy transferred from the collector to the heat transfer medium to the incident radiant energy on the collector. A quantitative comparison [6] between various solar collectors (Fig. 1) indicates that the efficiency is particularly dominated by the radiation losses. The losses in concentrating type of collector are more due to its open collector area. The efficiency for a certain collector is not a fixed value, but rather it is dependent on the location, temperature, wind speed, etc [7,8].

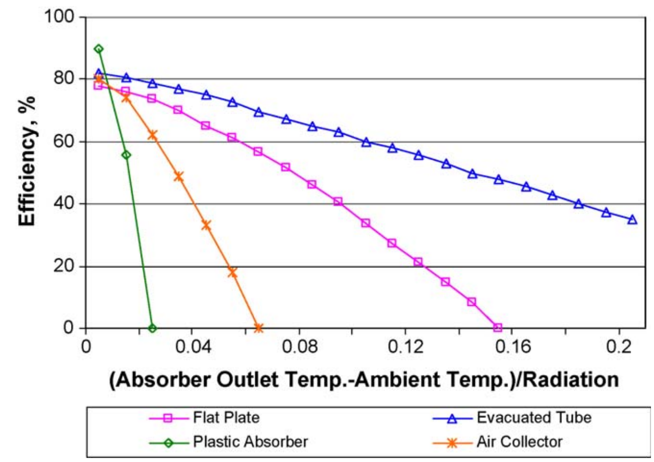

Fig. 1. Collector efficiency curves for various types of collectors [6].

Sodha et al. [9] have studied and compared the hourly thermal performance of three built in storage solar water heaters with different designs each of 100 l capacity. Design I consists of three tanks connected in series; in Design II, a parallelepipedic tank is divided into five zones with baffles; Design III is a simple parallelepipedic tank. The first two designs help in inducing thermal stratification in the tank. They concluded that the performance of Design II is the best of the three designed systems. Sodha et al. [10] have also studied the thermal performance of multi-tank (three-tank) solar water heating system under six climatic conditions, characterized by the solar fraction (fraction of needed energy available from sun). They concluded that the solar fraction in the proposed design was more than that in conventional solar water heaters and was more economical.

Huang and Du [11] suggested that the overall performance rating of a thermosyphon solar water heater should include the thermal performance of the system during the energy-collecting phase and the system cooling loss during the cooling phase. Conventionally, the overall performance rating of a thermosyphon solar water heater considers the thermal performance of the system during the energy-collecting phase and the system cooling loss during the cooling phase. Chang et al. [12] suggested that the performance rating should also take the heat removal efficiency of the system during the system application phase into consideration. As discussed by Belessiotis and Mathioulakis [13], Henden et al. [14] and Kubler et al. [15], the thermal performance of a system refers only to its performance during the energy-collecting phase when solar radiation is incident upon the system collectors, i.e. it does not indicate the actual amount of useable energy that a user will receive from the system. This amount of energy is determined by the mixing effects of the hot water in the storage tank and the cool charge water, which flows into the storage tank during the system application phase. Knudsen [16] investigated the influence of the storage tank volume upon the thermal performance of solar direct hot water systems. His study emphasized the importance of system utilization from the consumer's point of view, and established a relationship between the energy consumed by the user and the volume of the storage tank. However, the heat removal efficiency of the storage tank during the hot water draw-off phase or the system application phase was not considered.

3. Classification on the basis of type of storage

3.1. Sensible heat storage type solar water heater

The storage is based on the temperature change in the material and the unit storage capacity is equal to the product of heat capacitance and temperature change. Sensible heat storage systems utilize the heat capacity and the change in temperature of the material during the process of charging and discharging. The amount of stored heat depends on the specific heat of the medium, the temperature change, and the amount of the storage material.

$$Q = mC_P(T_f - T_i) = mC_P dT \tag{1.1}$$

where Q is the heat stored, m is the mass, C_p is the specific heat and dT is the temperature difference between initial, i and final, f temperatures.

Sensible heat storage type solar water heater uses water as heat transfer fluid and storage medium. The best example of this type of the conventional type of solar water heaters used in India is flat plate solar water heaters.

First commercial solar water heater, the Climax (Fig. 2), was patented by Clarence M. Kemp in 1891 [17,18]. His solar water heating system consisted of a metal tank within a glass covered wooden box. This water heater was used to produce water hotter than 38.8 °C on sunny days. Kemp's concept is still in use today in the form of integral collector storage solar water heaters. A diagram of Kemp's design is shown in Fig. 2. William Bailey advanced the art of solar water heating in 1909 [17,18] by separating the solar water heater into two separate components: a solar heat collector and a water storage tank. Bailey's system was the first to use an insulated storage tank relied upon the thermosyphon principal to circulate water between the solar collector and a storage tank.

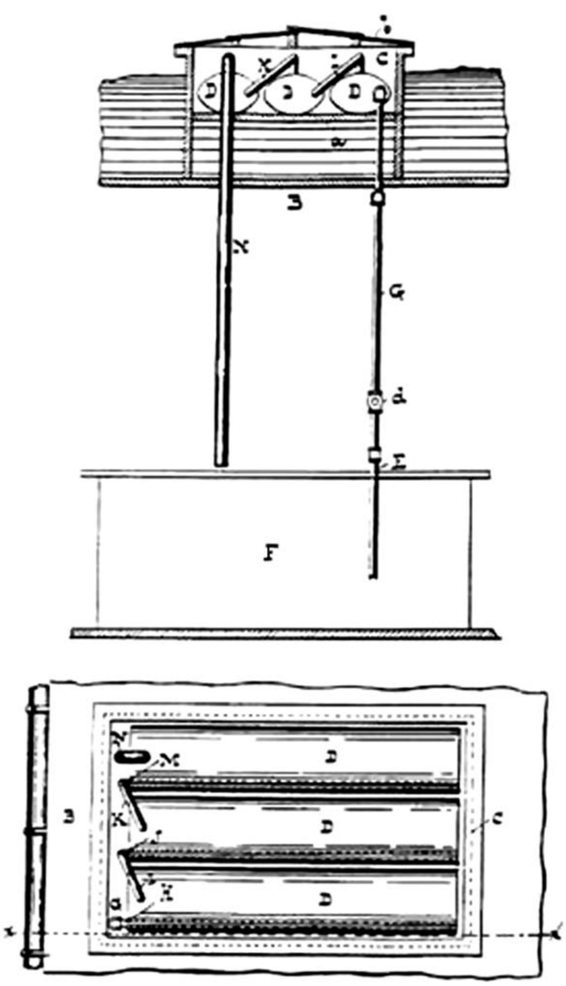

Fig. 2. World's first commercial solar water heater.

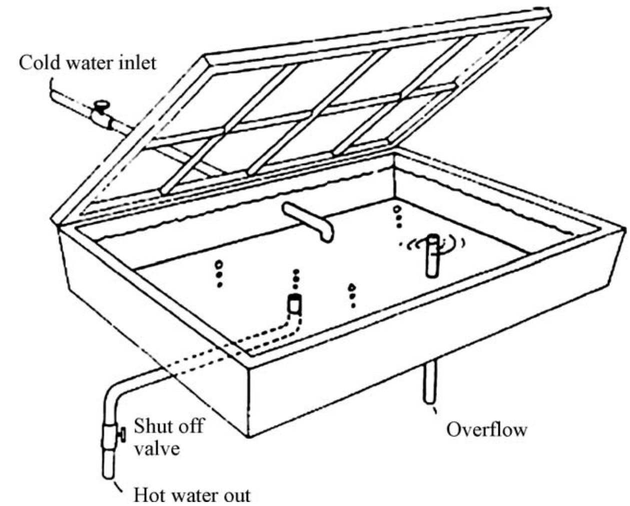

Fig. 3. Japan's first solar water heater invented by Yamamoto [17,18].

Yamamoto in 1947 [17,18] had designed Japan's first commercial solar water heater (Fig. 3) by getting inspiration by noticing a large bath tub full of water covered by a sheet of glass left out in the sun all day while visiting a rural area. In the late 1950s, the 'closed-pipe' system on which many modern Japanese units are based was introduced.

Husain et al. [19] theoretically analyzed a model of solar collector/storage water heater in which water flow at a constant rate between glass cover and the absorber plate. The effect of the variations of the depths of water, its flow rate and the length of the absorber plate on the performance was studied. They concluded that if these parameters could be known then it becomes easier to design a solar collector/storage water heater. Rosen et al. [20] discussed the use of exergy analysis rather than energy analysis for evaluation of the performance of sensible heat storage systems. He developed relationships to two different thermal storage systems, each of which undergoes a similar charging process. For the first system, heat was recovered from the storage after one day by a stream of 5000 kg of water entering at 25 °C and leaving at 35 °C; for the second system, heat was removed from the storage after 100 days by a steam of 100 kg water entering at 25 °C and leaving at 75 °C. The comparison between the performance of the two systems showed that the energy efficiency of the two systems was the same, while the exergy efficiencies of the first and the second systems were 26.70% and 72.80%, respectively. A flat plate collector has been very well studied and their performance equations are known as Hottel Whillier Bliss equation [21].

3.2. Latent heat storage type solar water heater

In the sensible heat storage type of storage, the temperature of the medium changes during charging or discharging of the storage, whereas in the latent heat storage type the temperature of the medium remains more or less constant since it undergoes a phase transformation. The latent heat storage systems offer high storage capacity as compared to sensible heat storage and also involve low heat losses. The importance and viability of the latent heat storage systems have been discussed extensively in literature [22–32].

Phase change materials are latent heat storage materials. The thermal energy transfer occurs when a material changes from solid to liquid or liquid to solid. They store 5–14 times more heat per unit volume than sensible storage materials such as water, masonry or rock. It is based on the heat absorption or release when a storage material undergoes a phase change from solid to liquid or to gas or vice-versa. The storage capacity of the latent heat thermal energy storage (LHTES) system with a PCM medium is given by

$$Q = mL + \int_{\mathrm{i}}^{\mathrm{m}} mC_{\mathrm{p,s}} \mathrm{d}T + \int_{\mathrm{m}}^{\mathrm{f}} n \tag{1.2}$$

where m is the mass, $C_{\mathrm{p,s}}$, $C_{\mathrm{p,l}}$ is the specific heat of PCM in solid and liquid phase, i, m & f are initial, melting and final temperature, dT is the temperature rise.

Kumar [33] designed, developed and evaluated the performance of a latent heat storage unit for evening and morning hot water requirements, using a box type solar collector. His system consisted of three finned heat exchangers (Fig. 4). Paraffin wax (melting temperature 54 °C) was used as a latent heat storage material and found that the performance of the latent heat storage unit in the system was very good to get the hot water in the desirable temperature range. Experiments were conducted for 15 l and 20 l of water.

Shukla [34] has designed two solar water heaters with paraffin as thermal energy storage material. One system had tank in tank type storage (Fig. 5) and the second had integrated type of storage using a reflector. The two systems were able to deliver hot water during the night and in morning on a 24 h cycle basis the two systems were found to be 45% and 60% efficient respectively. Galenen and Vanden [35] also used paraffin for domestic hot waters and space heating.

Lane [36] studied ammonium alum ($NH_4Al(SO_4)_2{\cdot}12H_2O$, MP 95 °C) for water heating system. Hasan et al. [37–39] have investigated some fatty acids as PCMs for domestic water heating. They recommended that myristic acid, palmitic acid and stearic acid, with melting temperature between 50–70 °C are the most promising PCMs for water heating.

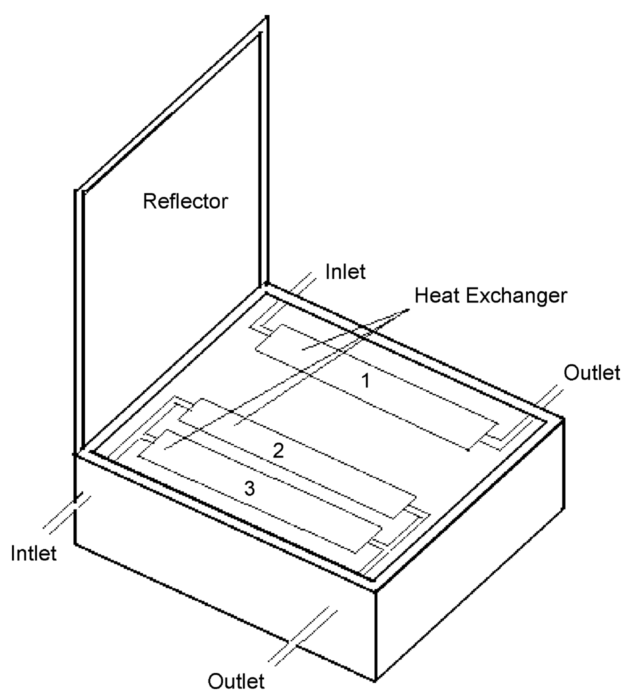

Fig. 4. Solar water heater designed by Kumar [33].

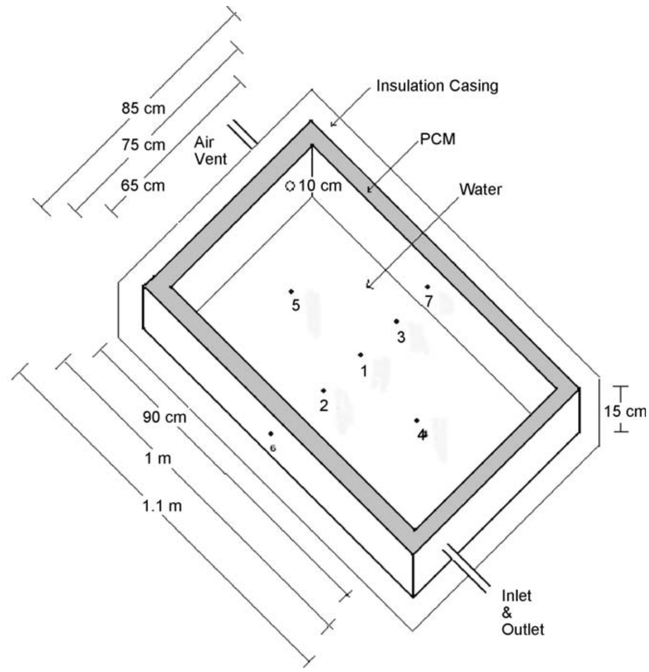

Fig. 5. Solar water heater designed by Shukla [34].

Prakash et al. [40] analyzed a built in storage type water heater containing a layer of PCM filled at the bottom, his design is shown in Fig. 6. During sunshine hours, the water gets heated up which in turn transfers heat to the PCM below it. The PCM collects energy in the form of latent heat and melts. During off sunshine hours, the hot water is withdrawn and is substituted by cold water, which gains energy from the PCM. The energy is released by the PCM on changing its phases from liquid to solid; this type of system may not be effective due to the poor heat transfer. A cylindrical storage unit in the closed loop with a flat plate collector has been theoretically studied by Bansal and Buddhi [41] for its charging and discharging mode. The calculations for the interface moving boundary and fluid temperature were made by using paraffin wax (P-116) and stearic acid as phase change materials.

Tiwari et al. [42] presented an analysis of PCM storage for a water heater by incorporating the effect of water flow through a parallel plate placed at the solid–liquid interface. In order to reduce the night heat losses from the exposed surface, a provision of covering the system by movable insulation was made. They concluded that the hot water (15–20 °C > ambient air temperature) can remain throughout the day and night, and the fluctuations in water temperature decrease with an increase in the melted region of the PCM.

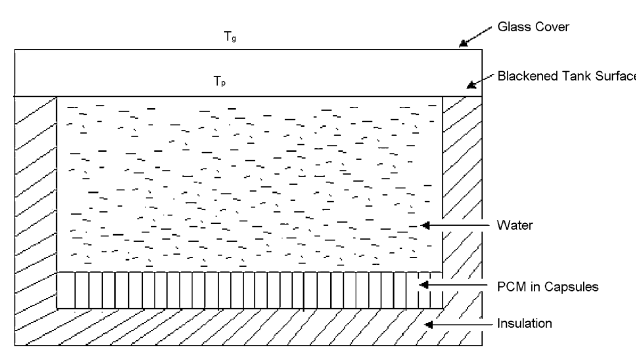

Fig. 6. Solar water heater designed by Prakash et al. [40].

A comparative study of solar energy storage systems based on the latent heat and sensible heat technique has been carried out to preserve the solar heated hot water for night duration by Chaurasia [43]. He used paraffin wax as PCM for solar water heating. For this purpose, two identical storage units were used; one unit contained 17.5 kg paraffin wax (melting temperature 54 °C) as the storage material packed in a heat exchanger made of the aluminium tubes and another unit simply contained the water as a storage material in a galvanised tank. Both units were separately charged during the day with the help of flat plate solar collectors having same absorbing area. This study revealed that the latent heat storage system comparatively yields more hot water on the next day morning as compared to sensible storage system.

Ghoneim [44] made a comparison between different sized latent heat storage vessels and sensible heat storage in a water tank with different degree of stratification. The storage vessel consists of a number of closed cylindrical pipes filled with the phase change medium, surrounded by heat transfer fluid. Bajnoczy [45] studied the two-grade heat storage system (60–30 °C and 30–20 °C) based on calcium chloride hexahydrate and calcium chloride tetrahydrate. They also studied the storage capacity changes during the cycles and possible use of a solar energy storage system for domestic water heating system. Kaygusuz [46] conducted an experimental and theoretical study to determine the performance of phase change energy storage materials for solar water heating systems with $CaCl_2 \cdot 6H_2O$ as phase change material. They also compared the performance of PCM, water and rock based storage system. Whenever solar energy is available, it is collected and transferred to the energy storage tank that is filled by 1500 kg encapsulated PCM. It consisted of a vessel packed in the horizontal direction with cylindrical tubes. The energy storage material ($CaCl_2 \cdot 6H_2O$) is inside the tubes made of PVC plastic and heat transfer fluid (water) flow parallel to them.

Boy et al. [47] proposed an integrated collector storage systems based on a salt hydrate phase change materials as an appliance for providing hot water instantaneously. They demonstrated that the thermal efficiency of such systems could be improved significantly by incorporating an appropriate PCM device. However, in their system the salt hydrate PCM was encapsulated in a special corrugated fin heat exchanger, which increased the cost of the system.

Rabin et al. [48] designed an integrated solar collector storage system (Fig. 7) based on salt hydrate. He used a salt hydrate eutectic mixture (48% $CaCl_2$, 4.5% KCl, 0.4% NaCl and 47.1% H_2O with a nucleating agent $BaCl_2 \cdot 2H_2O$ by 1% weight and phase transition temperature of 27–29 °C, latent heat of fusion 164 kJ kg^{-1}). He concluded that the PCM layer had a major role on the location of the propagation distance of the solid interface of the solid–liquid PCM interface and minor influence on the liquid interface.

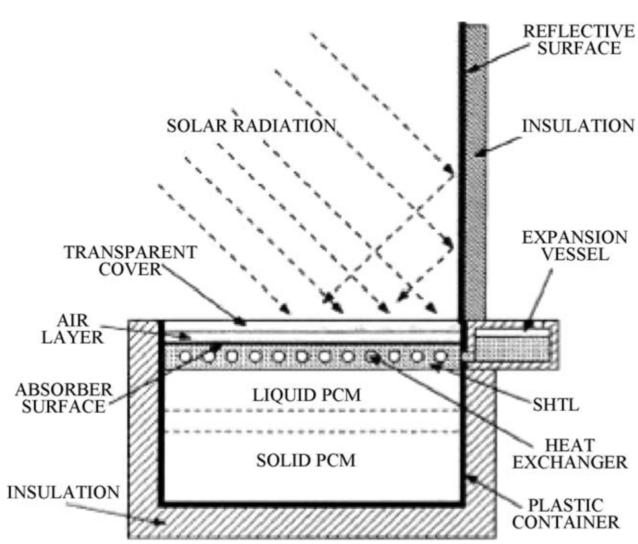

Fig. 7. Integrated solar collector storage system designed by Rabin et al. [48].

Tayeb [49] developed a system for domestic hot water using $Na_2SO_4 \cdot 10H_2O$ as a PCM and compared it with the simulation model that gives the optimum flow rate of the inlet water supply required to maintain the constant-temperature water at the outlet. Font et al. [50] conducted a preliminary study for the design of a device for a domestic water heater using a solid–solid PCM. Numerical simulation has been made using a unidirectional model and verified with the experimental results. The concordance between both experimentally and simulation results shows that this model is available to study the heat transfer phenomenon in the PCM in order to optimize the design of the device. Bhargava [51] studied theoretically a solar water heater with PCM and concluded that the efficiency of the system and the outlet water temperature during the evening hours increases with the increase in the thermal conductivity of the solid–liquid phases of the materials.

Canbazoglu et al. [52] compared solar water heating systems with PCMs to conventional solar water heating systems (Fig. 8). Polyethylene bottles were filled with a PCM and set into the tank as three rows. The total mass of PCM used in the heat storage tank was approximately 180 kg. The results indicate that the water temperature has a constant value of 46 °C during the night until sunrise, as the hot water was not consumed. The difference between the temperatures at the midpoint of the heat storage tank and at the outlet of the collector of the heat storage tank with the PCM is greater, by an average value of approximately 6 °C, than that of the system without a PCM. This temperature difference is considerable, exhibiting the high heat storage performance of the heat storage system with a PCM. The storage time of hot water, the mass of hot water produced to use, and the total heat accumulated in the heat storage tank that contains some hydrated salts were

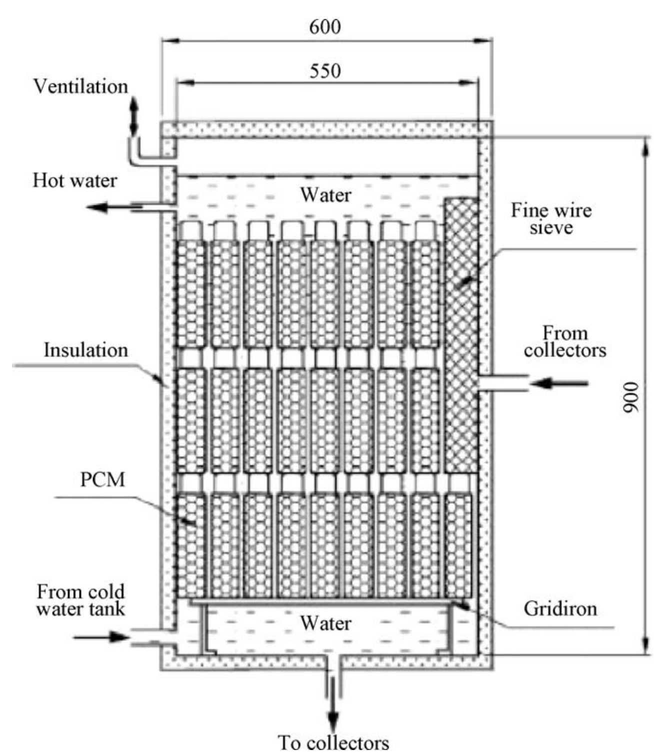

Fig. 8. Cross-section of the storage unit designed by Canbazoglu et al. [52].

approximately 2.59–3.45 times greater than that of conventional solar energy systems with a heat storage tank that does not include a PCM. The thermal performances of hydrated salt-PCMs such as $Na_2S_2O_3{\cdot}5H_2O$, $Zn(NO_3)_2{\cdot}6H_2O$, $Na_2HPO_4{\cdot}12H_2O$, $CaCl_2{\cdot}6H_2O$ and $Na_2SO_4{\cdot}10H_2O$ were examined theoretically. The size and shape of the vessel have a significant effect on the collection of solar radiation. The greater the exposed surface area to volume ratio the less time will be required for insolation to heat up the water store. For example, for a shallow rectangular vessel with a high surface area/volume ratio, the incident insolation has a small depth of water to heat up. However, a store with a large exposed surface area will also lose substantial amounts of heat by convection and long-wave radiation during normal conditions and will cool down significantly by radiative losses to the night sky. The importance of the surface area–volume ratio was realised by Haskell [53] who patented an 'improved' integrated collector storage solar water heater design that used a shallow rectangular tank having an inherently higher surface area to volume ratio than cylindrical vessels.

This design yielded a successful product with a more rapid warm-up in the morning and hotter water on partially cloudy days. Japanese research in the 1940s concentrated on rectangular tanks in open-type collectors and cylindrical vessels. The latter developed into long thin closed-pipes. Both systems had small surface area to volume ratios when compared to designs from the USA. Subsequent work in Japan, in the 1970s, stayed with this proven concept. Chinnappa and Gnanalingan [54] used coiled galvanised pipes have also been employed as storage vessels. The heat removal efficiency of a system during its application phase is an important consideration when assessing the overall thermal performance of the system since it enables the direct evaluation of the energy, which will be made available to the user.

4. Conclusion

The above review shows that great efforts have been made by researchers to develop solar water heaters. A vast range of PCMs and technology is available for the development and use of solar water heaters. This review will help in designing of suitable heat exchange mechanism with latent heat thermal energy storage for solar water heaters. Potential materials used by researchers as potential PCMs in solar water heaters were described. Still the designs were of preliminary in nature and no commercial design and system is available in the international market. An inbuilt thermal storage can be an alternative to the present day solar water heater with less complicated design and cost effectiveness.

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